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Super B Factories

D G HITLIN
Lauritsen Laboratory, California Institute of Technology, Pasadena, CA 91125, USA
E-mail: hitlin@slac.stanford.edu

Abstract. Heavy-flavor physics, in particular B and τ physics results from the B factories, currently provides strong constraints on models of physics beyond the Standard Model. A new generation of colliders, Super B Factories, with 50 to 100 times the luminosity of existing colliders, can, in a dialog with LHC and ILC, provide unique clarification of new physics phenomena seen at those machines.

Keywords. B factory; CP violation; B meson; supersymmetry.

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1. Introduction

The two asymmetric B factories, PEP-II and KEK-B, and their companion detectors, *BABAR* and Belle, have produced a wealth of flavor physics results, subjecting the quark and lepton sectors of the Standard Model to a series of stringent tests, all of which, as of this writing, have been passed.

By measuring *CP*-violating asymmetries in the B meson system for the first time, PEP-II/*BABAR* and KEK-B/Belle have shown that the CKM phase accounts for all *CP*-violating phenomena in $b \to c\bar{c}s$ and $b \to u\bar{u}d$ decays (see figure 1) [1]. While the *BABAR* and Belle measurements have placed stringent constraints on physics beyond the Standard Model, there is a substantial literature demonstrating that new physics beyond the Standard Model, be it supersymmetry, extra dimensions, or other Standard Model extensions, can have measurable effects in the flavor sector. Measuring these effects typically requires data samples substantially larger than the current B Factories will provide. Some of these measurements are accessible at the LHC [2], but the most promising approach to this physics would be a very high luminosity asymmetric B Factory, a Super B Factory.

2. Physics motivation and capability

The current B Factories will integrate a combined luminosity of $\sim$2 ab^{-1}, which will improve the present knowledge of SM related quantities and will allow more stringent bounds on new physics (NP) parameters. This precision is not, however, sufficient to measure new physics effects. Many tens of ab^{-1} are required to isolate

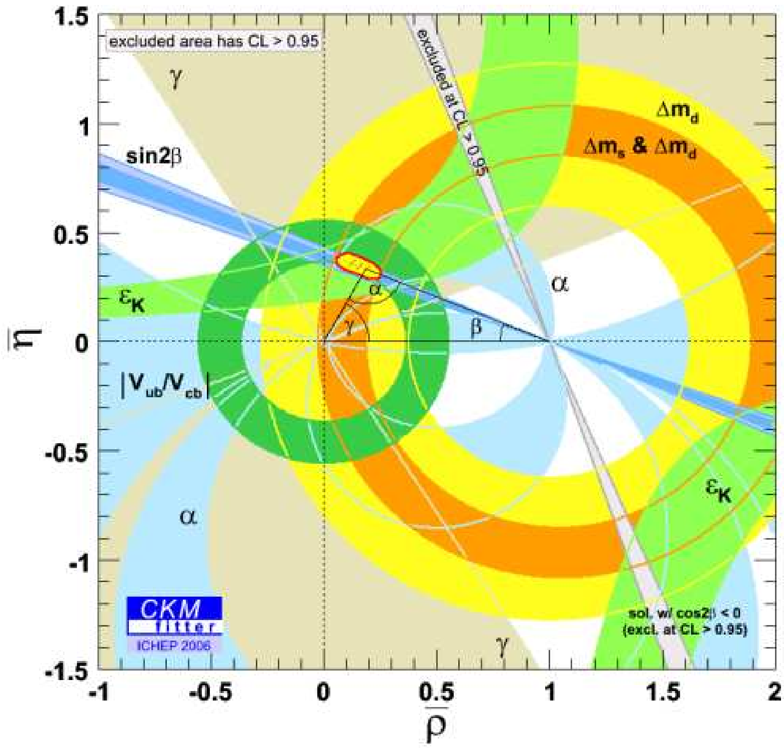

Figure 1. The status of unitarity triangle-related measurements as of the ICHEP 2006 conference.

unambiguous new physics effects. A Super B Factory at a luminosity of 10^{36} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ can collect 15 ab^{-1} in a new Snowmass year, or 75 ab^{-1} in five years. The new Snowmass year is an update of the convention that multiplying peak luminosity by a 'year' containing 10^7 s provides a good measure of actual running time, the effects of accelerator and detector down time, dead time effects and the difference between peak and average luminosity. PEP-II/*BABAR* and KEKB/Belle experience has shown that a 'new snowmass year' with 1.5×10^7 s is a better estimator of actual performance at a B factory.

A data sample this large will make the unitarity triangle tests, in their various versions, a genuine precision test of the Standard Model. However, it is likely that new physics effects will in fact manifest themselves in other areas, which we will discuss in the following section [3].

2.1 *Measurements of* $\sin 2\beta$ *with penguin-mediated decays*

A primary tool for isolating new physics is the time-dependent analysis of decay channels that can only proceed through penguin diagrams, such as the $b \to s\bar{s}s$

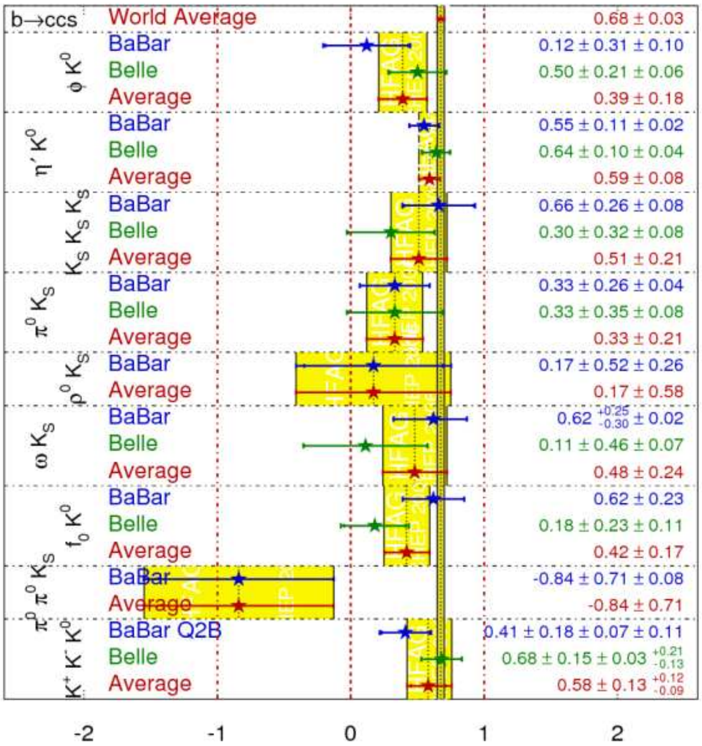

Figure 2. *CP* asymmetries in $b \to s\bar{s}s$ decays, compared with the world average for $b \to c\bar{c}s$ decays, as of the ICHEP 2006 conference (HFAG preliminary).

processes $B^0 \to \phi K^0$ and $B^0 \to (K\bar{K})_{CP} K^0$ or the similar $b \to d\bar{d}s$ transitions $B^0 \to \eta' K^0$, $B^0 \to f_0 K^0$, $B^0 \to \pi^0 K^0$, $B^0 \to \rho^0 K^0$, $B^0 \to \omega K^0$, and $B^0 \to \pi^0 \pi^0 K^0$.

The dominant contribution to these decays is the combination of CKM elements $V_{tb} V_{ts}^*$ and these amplitudes have the same phase as the charmonium channels $b \to c\bar{c}s$, up to a small phase-shift of V_{ts} with respect to V_{cb}. New heavy particles contribute new loop amplitudes, with new phases that can contribute to the *CP* asymmetry and the S coefficient of the time-dependent analysis could be substantially different from $\sin 2\beta$. The comparison between results from all the above B^0 decay channels and $\sin 2\beta$ from charmonium is shown in the HFAG [4] plot in figure 2.

For this comparison, one has to take into account a Standard Model uncertainty due to a penguin contribution with an up quark running in the loop [5,7,8]. Using the CKM couplings to scale this term to the leading contribution, we obtain a correction of order $\lambda^2 \simeq 5\%$, coming from the fact that these contributions are doubly Cabibbo-suppressed in the case of the theoretically cleanest channels $B^0 \to \phi K_S^0$ and $B^0 \to K_S^0 K_S^0 K_S^0$.

Table 1. Measurement precision for *CP* asymmetries in rare decays sensitive to new physics.

CPV in rare decays		e^+e^- Precision (%)		
Measurement	Goal	2/ab	15/ab	75/ab
$S(B^0 \to \phi K_S^0)$	$\simeq$5%	19.6	7.1	3.2
$S(B^0 \to \eta' K_S^0)$	$\simeq$5%	7	2.5	1
$S(B^0 \to K_S^0 \pi^0)$		10	3.7	1.6
$S(B^0 \to K_S^0 \pi^0 \gamma)$	SM: $\simeq$2%	13.5	4.9	2.2
$A_{CP}(b \to s\gamma)$	SM: $\simeq$0.5%	1.2	0.4	0.2
$A_{CP}(B \to K^* \gamma)$	SM: $\simeq$0.5%	0.7	0.3	0.1

For the other decay channels, the uncertainty could be 10% or more, since in that case the doubly Cabibbo-suppressed terms also include tree-level transitions. Once these contributions are taken into account, one can use the experimental results for the S parameters to obtain a bound on new physics parameters. For example, one can use the knowledge of $b \to s\gamma$ and $b \to s\ell\ell$ branching ratios in SUSY models to bound the values of NP parameters and study their effect on the $b \to s$ penguin modes.

The B factories have explored many channels, most with poor statistics. It is clear that we are potentially at the beginning of a very interesting era in which we can begin to probe new physics effects beyond the Standard Model in the flavor sector. To do this, the statistical error has to be reduced to the level of the theoretical uncertainties. This requires a data sample 20 and 50 times larger than present (i.e. 20 to 50 ab^{-1}). In a few years, with LHC running and just before the beginning of the ILC project, a program of precision measurement at a Super B Factory with a capability of delivering more than a few tens of billions of $B\bar{B}$ pairs, will be complementary to LHC physics. For example, the precise measurement of channels mediated by loop diagrams, both in $b \to s$ and $b \to d$ transitions, will allow the determination of the couplings for new physics contributions, such as the mass insertion parameters δ^{23} and δ^{13} in SUSY scenarios [6]. For instance, a mass insertion δ^{23} with an imaginary part of $\sim$2%, with an average squark mass in the range $\sim$350–450 GeV can produce a deviation of $S(\phi K_S^0)$ of the order of 20% with respect to $S(J/\psi K_S^0)$. In order to establish a 20% difference at the 5σ level, *i.e.* measuring $A_{CP}(\phi K_S^0) = 0.60 \pm 0.03$, and assuming the current per event sensitivity, we need a statistical precision corresponding to at least 30 ab^{-1}.

Other constraints on NP can be obtained by studying similar channels, summarized in table 1. For instance, the radiative penguin decays $b \to s\gamma$ provide a particularly clean environment. Direct *CP* violation in these decays is expected to be <0.5% in the Standard Model, but could be enhanced by new physics contributions to the penguin loop. Recent inclusive and exclusive measurements are just beginning to constrain such contributions. The information they provide at this point exclude the possibility of huge variations with respect to the Standard Model expectations. However, because of the limited statistics, the possibility of observing an enhancement of an order of magnitude still exists; only a Super B

Table 2. Measurement precision for rare decays sensitive to new physics.

Rare decays		e^+e^- Precision		
Measurement	SM	2/ab	15/ab	75/ab
$\sqrt{\mathcal{B}(b\to d\gamma)/\mathcal{B}(b\to s\gamma)}$		23%	8.5%	3.8%
$\mathcal{B}(B\to D^*\tau\nu)$	8×10^{-3}	12.2%	4.5%	2%
$\mathcal{B}(B\to s\nu\bar{\nu})(K^{-,0}, K^{*-,0})$	4×10^{-6}	$\sim 1\sigma$	$>2\sigma$	$>4\sigma$
$\mathcal{B}(B_d\to\text{invisible})$		2.5×10^{-6}	9×10^{-7}	4×10^{-7}
$\mathcal{B}(B_d\to\mu\mu)$	8×10^{-11}	3.7×10^{-8}	1.4×10^{-8}	6×10^{-9}
$\mathcal{B}(B_d\to\tau\tau)$	1×10^{-8}	1.2×10^{-3}	5×10^{-4}	2×10^{-4}
$\mathcal{B}(\tau\to\mu\gamma)$			$\sim$ few $\times 10^{-8}$	$\sim 10^{-8}$

Factory can provide the required statistics. With larger samples it would be interesting to measure the direct *CP* asymmetry in $b \to d$ decays, where the Standard Model prediction is -12%. New physics couplings with opposite helicity can be explored by studying the photon polarization in $b \to s\gamma$ transition, measuring, for example, time-dependent *CP* violation in $B^0 \to K^{*0}(\to K^0_S\pi^0)\gamma$, or the Dalitz plot distribution of the $K\pi\pi$ system in $B^0\to K\pi\pi\gamma$. Both measurements will continue to be statistically limited even at 75 ab^{-1}.

2.2 *Rare decay branching fractions*

Many rare B decay modes can potentially give access to physics beyond the Standard Model via measurements other than the *CP*-violating asymmetries. Some examples of these modes are listed in table 2. Typically, these decays do not occur at tree level, and thus the rates are strongly suppressed in the Standard Model. Substantial enhancements in the rates and/or variations in angular distributions of final state particles could result from the presence of new heavy particles in loop diagrams, resulting in clear evidence of new physics. Moreover, because the pattern of observable effects is highly model-dependent, measurements of several rare decay modes can provide information regarding the source of the new physics.

The ratio of $b \to d\gamma$ to $b \to s\gamma$ decays is directly related to the ratio $|V_{td}/V_{ts}|$. It is interesting to measure this ratio in penguin processes as well as through B_d and B_s mixing, since new physics enters in different ways. The ratio of the exclusive decays $B \to \rho\gamma$ and $B \to K^*\gamma$ can be accurately measured, but the precision of the determination of $|V_{td}/V_{ts}|$ is limited by theoretical uncertainties of $\sim$10% in the ratio of the form factors. A measurement of the ratio of the inclusive decays does not suffer from this uncertainty, but is experimentally rather challenging, and requires a large data sample. Searches for $b \to s\nu\bar{\nu}$, either inclusively or exclusively, are extremely difficult, due to the presence of the two final-state neutrinos. The required sensitivity can, however, be obtained using the recoil method, in which the signal mode (in this case the exclusive $B \to K\nu\bar{\nu}$ and $K^*\nu\bar{\nu}$ modes) is sought in the recoil against a fully reconstructed hadronic B decay. Assuming Standard Model branching fractions, we would expect a signal of 10 events in each of the

Table 3. Measurement precision for observables in $s\ell^+\ell^-$, $K\ell^+\ell^-$, and $K^*\ell^+\ell^-$ decays.

$B \to s\ell^+\ell^-$ decays	e^+e^- Precision (%)		
Measurement	2/ab	15/ab	75/ab
$\mathcal{B}(B \to K\mu^+\mu^-)/\mathcal{B}(B \to Ke^+e^-)$	$\sim$10	3.6	1.6
$A_{CP}(B \to K^*\ell^+\ell^-)$			
All	7.3	2.7	1.2
High mass	14.7	5.4	2.4
$A_{\mathrm{FB}}(B \to K^*\ell^+\ell^-)$			
$\hat{s}_0$	24	9	4
$A_{\mathrm{FB}}(B \to s\ell^+\ell^-)$			
$\hat{s}_0$	33	12	6
$C_9,\ C_{10}$	44–67	16–25	7–12

four modes ($K^{-,0},\ K^{*-,0}$) although with a substantial background, with 3 ab^{-1} of data. A statistically significant signal would emerge in the combination of modes with approximately 10 ab^{-1} even using a simple cut-and-count analysis.

The decays $B_d \to \ell\ell$ ($\ell = e,\ \mu,\ \tau$) are somewhat less promising, in the sense that it appears impossible to reach the predicted Standard Model branching fractions even with more than 75 ab^{-1} of data. Moreover, $B_d \to \mu\mu$ is expected to be accessible at LHCb, which will also be able to measure $B_s \to \mu\mu$, which is expected to provide a more stringent test of new physics. However, even 10 ab^{-1} of data will improve the existing limits on these modes by an order of magnitude, and an e^+e^- B factory does have the advantage of also being able to search for $B_d \to e^+e^-$ and the (extremely challenging) $B_d \to \tau^+\tau^-$ modes.

2.3 $B \to K\ell^+\ell^-$ *and* $K^*\ell\ell$ *decays*

The exclusive $K^{(*)}\ell\ell$ and inclusive $s\ell\ell$ decays have been intensively studied theoretically, as they provide a potentially unique window on new physics. For example, in the Standard Model, the forward/backward asymmetry A_{FB} of the lepton pair has a zero at lepton pair mass $\hat{s}_0 = 0.14$ GeV. In extensions of the Standard Model, this zero may be approached from the opposite direction, or may be altogether absent. This region of lepton pair invariant mass represents only a small fraction of the allowed kinematic region of these rare decays, so a large data sample is required to make this measurement. The measurement of A_{FB} can be done at hadronic experiments, but only in the exclusive modes involving muons. Theoretical predictions are typically more precise for inclusive processes, which can only be measured at a Super B Factory. It is very important to compare A_{FB} in muon and electron modes, as this asymmetry can be changed by the presence of a charged Higgs. Table 3 summarizes the achievable measurement precision.

2.4 *τ and charm physics*

At B factories there are roughly as many τ's and charmed particles produced as B^0s. The lepton flavor violating process $\tau \to \mu\gamma$ can be constrained at the 10^{-10} level with a 50 ab^{-1} data sample. Another important aspect to stress is the strong connection of B and τ physics, in the framework of testing GUT models. In general, with the high integrated luminosity that a Super B Factory can collect, rare decays of τ leptons can be studied with high precision, providing a stringent test of flavor violation in the leptonic sector and boosting our capability of testing GUT models. Finally, the possibility of producing polarized electron beams opens interesting possibilities for measuring the τ electric dipole moment by comparing the mean value of T-odd observables for opposite values of the polarization. The current sensitivity of 10^{-16} cm for $F_\tau/2m_\tau$ could be improved by four orders of magnitude by using polarized beams at a Super B Factory.

Extremely interesting limits can be set at a Super B Factory on $D^0\bar{D}^0$ mixing, as well as on rare flavor-changing neutral current decays.

3. Super *B* Factories

Given the strong physics motivation, there has been a great deal of activity aimed at producing an e^+e^- B factory that can produce samples of B mesons 50 to 100 times larger than that will exist when the current B factory programs end.

3.1 *Super PEP-II and Super KEK-B*

Upgrades of PEP-II [9] and KEK-B [10] to Super B Factories that accomplish this goal have been proposed at SLAC and at KEK. These machines are reasonable extrapolations of the existing facilities, but they use a great deal of power, and pose substantial challenges for detectors. As SLAC will have no on-site accelerator-based high energy physics in the coming decade, the Super PEP-II proposal is moribund. As of this writing, no decision has been made on Super KEK-B.

These Super B Factory proposals have much in common, but differ in important ways. A comparison of important parameters is shown in table 4. In order to reach luminosities approaching 10^{36} cm^{-2} s^{-1}, currents in the range of 10 A are required. This necessitates filling every RF bucket, and in the case of Super PEP-II, doubling the RF frequency. Very small β_y^* values, from 1.5 to 3 mm are employed. In the case of Super KEK-B, a factor of two increase in luminosity is assumed for the use of crab crossing, which will soon be tested at KEK-B.

These upgrades of the current asymmetric B factories to much higher luminosities are conservative in the sense that they are firmly rooted in two very successful colliders, and break little new ground in accelerator physics. The high circulating currents present a formidable engineering challenge, and result in high power consumption (of the order of 100 MW), larger detector backgrounds and higher radiation levels. *BABAR* and Belle have projected backgrounds and radiation levels based on their current experience; in both cases replacement of several detector

Table 4. Parameters of current B factory and Super B Factory designs.

Machine	Crossing angle (mrad)	ξ_y	e^+e^-/ bunch $\times 10^{10}$	$I+$ (mA)	$I-$ (mA)	Power (MW)	β_y^* (mm)	E_H (GeV)	E_L (GeV)	Luminosity $\times 10^{36}$
PEP-II	0	0.068	8	2950	1750	22.5	11	9	3.1	0.10
KEK-B	± 15	0.065	5.8	1680	1290		6	8	3.5	0.16
Super PEP-II	0	0.12	10	4500	2500	90	1.7	8	3.5	7
Super KEK-B	0	0.28	12	9400	4100	>100	3	8	3.5	5
Super-B	± 15	0.045	3.3/1.9	1400	2500	23	0.2	7	4	10

subsystems would be required to function in a Super B Factory environment. The projections differ in important ways, however. *BABAR*, which has head-on crossing, sees a substantial background term dependent on luminosity, while Belle, with an angle crossing scheme, sees a much smaller luminosity term. This difference has been traced to overbent beam particles from the first dipole magnets of PEP-II, which cause off-energy electrons or positrons to hit within the detector. Thus an angle-crossing scheme, with a crabbed waist or crab crossing, is the preferred interaction region geometry for a Super B Factory.

3.2 *SuperB – A low emittance Super B Factory*

The problematic power consumption and background issues associated with the SLAC and KEK-based Super B Factory designs have stimulated a new approach to constructing a 10^{36} luminosity Super B Factory.

The starting point of this effort was an attempt to leverage the active development effort in support of a high energy linear collider that has been going on for the past two decades. The idea, which has antecedents dating to the mid-1980s [11], was to achieve high luminosity by using very low emittance beams with high disruption, but to recapture at least the positron beam and re-circulate it.

The advantages of a re-circulating linear collider (RLC) design are clear, but the challenges are formidable. There is a large circulating current in the damping ring(s), but, with bunch trains extracted using a fast kicker, the current at the interaction region is much smaller than in a conventional collider interaction region. The high luminosity is produced by having very small beam sizes and a high collision rate. Collisions take place in a regime in which there is a contribution to the center-of-mass energy spread from beam–beam interactions as well as from the energy spread of the incoming beams. It is, however, a substantial challenge to produce luminosities of the order of 10^{36} cm^{-2} s^{-1} while having center-of-mass energy spread less than 10 MeV. This has proven to be a difficult problem.

We have therefore considered another concept that also has its roots in ILC R&D: a very low emittance storage ring, based on the ILC damping rings and final focus, that incorporates several novel accelerator concepts and appears capable of meeting all design criteria, while reducing the power consumption, which dominates the operating costs of the facility, by a factor of three or four.

A new design, called Super$B$, has been produced by the Frascati/SLAC group and is under active consideration by INFN [12] for construction at a site near Frascati. Table 4 compares the basic parameters of Super$B$ to the older style Super B Factory designs.

By utilizing concepts developed for the ILC damping rings and final focus in the design of the Super$B$ collider, it is possible to produce a two-order of magnitude increase in luminosity with beam currents that are comparable to those in the existing asymmetric B factories. This means that only minor modifications to an existing B factory detector, such as *BABAR*, are needed. Background rates and radiation levels are expected to be comparable to current values; so detectors should operate, in the main, as they do currently. Some upgrades are, of course, desirable: the radius of the beam pipe should be reduced, allowing a first measurement of track position closer to the vertex and improving the vertex resolution (this allows the energy asymmetry of the collider to be reduced); the drift chamber should be replaced, as the current chamber will have exceeded its design lifetime; the endcap calorimeter should be replaced with faster crystals having a smaller Molière radius, since there is a large increase in Bhabha electrons in this region.

The Super$B$ design effort has imposed several constraints: the lattice is closely related to the ILC damping ring lattice, and as many PEP-II components as possible should be incorporated into the design. Many PEP-II components can in fact be re-used: The HER and LER magnets (with 96 additional LER dipoles required), the magnet power supplies, the RF system, the digital feedback system, and many vacuum components. This should reduce the cost and engineering effort needed to bring the project to fruition [13].

This Super B Factory concept is generating substantial interest in the physics community. It may, in fact, be the most promising approach to produce the very high luminosity asymmetric B factory that is required to observe and explore the contributions of physics beyond the Standard Model to heavy quark and τ decays. A letter of intent document, to be submitted to INFN in 2007, is in preparation.

4. Conclusions and outlook

The two first generation asymmetric B factories, PEP-II and KEK-B, were built after considering a wide variety of technical options for achieving very high luminosity with asymmetric energies. Both B factories have been very successful, handily exceeding design luminosity in a short time, and performing very reliably.

The associated detectors, *BABAR* and Belle, have utilized the very large data samples provided by PEP-II and KEK-B to provide a cornucopia of new heavy quark and heavy lepton physics measurements. These have subjected the Standard Model to new and stringent tests, all of which have thus far been passed.

With much larger data samples of 50–100 fb^{-1}, new physics effects in B and τ decays should be readily measurable, and could play a crucial and complementary role with the LHC and ILC in deciphering the details of, for example, supersymmetry breaking. Samples of this size require the construction of a Super B Factory to provide data at a rate exceeding 10 ab^{-1}/year.

Upgrades of PEP-II and KEK-B to Super B Factory capability have been explored, and are technically feasible, if difficult and expensive to operate. A new design, called Super$B$, employing approaches originally investigated for the ILC, appears to solve these problems. It has much lower power requirements, uses beam currents comparable to those of the existing B factories, and even reuses many existing components, including the detector. It is fully capable of providing the required luminosity, and even has upgrade capability.

Acknowledgments

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